IMPROVEMENT OF A MANUFACTURING PROCESS FOR SUSTAINABILITY USING MODELING AND SIMULATION

4162 Thesis

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Abstract

Sustainable manufacturing provides the opportunity for companies to reduce the environmental impact of their processes by producing more efficiently. This project studies the benefits of sustainable manufacturing and shows them in a case study. The methodology followed in the project starts with choosing a suitable manufacturing process from a factory; to observe and collect data from the process. Then, with the knowledge acquired of the manufacturing process, the next step is to build a model with a simulation software named Witness. The model is meant to work as the real manufacturing process in order to simulate some scenarios that will turn out the manufacturing process more sustainable. In order to quantify the improvements in the process, a section in the project defines some sustainable measures, such as, waste generation, energy consumption and GHG emissions. The project results in suggestions to reduce the environmental impact and improve the productivity of the manufacturing process for sustainable manufacturing .

Acknowledgments

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To Custom Castings Ltd. and, especially, to Dr. Angelito Velasco for giving me the opportunity to study a real manufacturing process from the factory and helping me to develop this project.

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CHAPTER 1: Introduction

This first chapter of the project focuses on the importance of sustainability, the project objectives and a briefly explanation of the methodology followed.

1.1 Background

Sustainability makes sure that current generations' actions are not compromising health and standards for future generations. Sustainable thinking is becoming important in human actions, such as manufacturing. Sustainability is a key word in this project, the goal of the project is to study a manufacturing process and to develop sustainable solutions; beneficial for both the company and the environment.

The existing industrial system calls for more goods than it used to. For example, there are 5 times more cars than those used to be in the 1950s, and people consume 20 times the plastic compared to in the 1950s [1]. Also, Americans now consume 222 pounds of meat per year, far from the 144 pounds they used to consume in the 1950s [1]. Therefore, people are starting to concern on the environmental impact of their actions and that is linked to sustainable manufacturing. If the goods that people need are produced following a sustainable manufacturing process, the global environmental impact will be reduced.

As said in the European Commission in 2008 [2], "as global living standards continue to rise; the challenge for manufacturing is to meet a constantly increasing demand for products whilst using less material, less energy and producing less waste." Since the manufacturing companies have to meet the demand for goods to keep on growing, it is reasonable to start thinking about more sustainable manufacturing processes. The aim of this project is to study a real manufacturing process and improve it in a sustainable way. In order to quantify the sustainability of the manufacturing process, some sustainable measures will need to be defined. For example, there have been some top worldwide companies that have made some improvements to reduce their environmental impact. They have quantified the reduction with the following measures: water usage, energy usage, CO_2 emissions, GHG emissions and amount recycled.

- Brandix, a worldwide clothing exporter, reduced water usage by 56% and energy usage by 46%, resulting also in a reduction of between 30% and 40% of its operating costs (Evans et al. 2008) [3].
- Ford reduced its energy usage by 30% and water usage by 43% in 2007 (Ford Motor Company, 2007) [2].
- Sony reduced its CO_2 emissions from electricity use and facility heating (European operations) by 93% over 10 years (Sony, 2010) [2].
- Rolls-Royce, the British engine manufacturing company, reduced greenhouse gas emissions by 24% and increased the proportion of solid waste sent for recycling by 63% over a period of 10 years (Rolls-Royce 2010) [2].

In these examples, companies quantify their sustainable improvements by using some sustainable measures. The sustainable measures used in this project will be further discussed and explained in this report. Some of them, such as greenhouse gases emissions and energy consumption, are the same as in these examples. Also, these examples show that improving a manufacturing process in a sustainable way not only benefits the environment, but also the revenue of the company by reducing its operating costs. Therefore, manufacturing companies will be keen on investing and developing sustainable manufacturing processes because it is attractive for them from an economic viewpoint.

1.2 Purpose and Scope

The objective of this project is to use the measure of sustainable manufacturing to reduce the environmental impact of a manufacturing process by producing more efficiently. In order to achieve sustainable manufacturing, the objective is to reduce all kind of waste existing in the manufacturing process. The different kinds of waste that I am referring to are defects, overproduction, waiting, non-value added activities, transportation, and excess motion. When observing and studying a manufacturing process with the purpose of increasing its sustainability it is important to be aware of all kinds of existing waste because every process is different and not the same kinds of waste will be found in different processes.

The manufacturing process is the center of attention in this project. All efforts to reduce waste and increase sustainability are done in the manufacturing process. Any previous stages like supply chain configuration, material selection, product design or any following stages like product use or product end of life are not covered. The purpose of the project is to study all the variables that play a role during the production process and see what modifications in these variables can increase the process' sustainability.

1.3 Thesis Layout

The methodology followed during the thesis development is explained in this section. In order to meet the objective of increasing a manufacturing process sustainability using modeling and simulation some previous steps were required.

The first important decision in the project development was to choose either to study a manufacturing process from literature or a real manufacturing process from a factory where I could have access. Fortunately, I had the opportunity to contact with a manufacturing company that allowed me to access the factory and study one of their manufacturing processes. Then, the next step was to decide which manufacturing process to study knowing that it had to meet some requirements. The manufacturing process had to have a cell layout, where the inputs and outputs in the process are clearly defined and every product follows the same steps during its fabrication. Also, the process had to be accessible, observable and with many operations to increase the probability to find waste and then be able to modify variables and develop solutions. Summarizing, the decision was made to facilitate the understanding and data gathering of the manufacturing process in order to be able to continue with the development of the thesis project.

Therefore, the next step was to observe the manufacturing process and collect the necessary data for the next step: build a virtual model with a computer software.

The following step has been already commented above, building a virtual model with a computer software. The software used is Witness 3.0 Manufacturing Performance Edition. The main reason to build a virtual model is because it gives the opportunity to easily modify the manufacturing process and see how modifications vary the inputs and outputs of the process. Witness has the necessary tools to model the machines and the flow of material between them. The rules that govern the system are set with variables and codes. Again, the relationship between this step and the previous step was very important to be able to codify the model in order to make it as similar as possible as the real manufacturing process in the factory.

With the virtual model verified and ready to use, the next step was to create scenarios modifying some of the variables of the manufacturing process. The observing step is very important when looking for ideas to create scenarios that change the process outputs. The different scenarios have been tested in the model by changing certain variables and simulating the process again. After the simulation, outputs were analyzed to see the advantages or disadvantages of the modifications. The outputs analyzed are productivity of the manufacturing process and resources utilization; machines and labor percentage of utilization. Then, in order to see the increase of sustainability of the process, those outputs are transformed to the sustainable measures defined above in the background section.

The final results of the project are the solutions developed after simulating different scenarios and analyzing their outputs. These solutions are the recommendations that I will do to the company operating the manufacturing process in order to increase its sustainability. The implementation of these solutions is out of the scope of the project and is not considered. Thus, the economic assessment of every suggested modification is not included in this project.

1.4 Literature Review

The previous research done on sustainable manufacturing explains the benefits of a sustainable manufacturing process and links environmental issues with financial performance. In order to show sustainable manufacturing as a benefit for a factory, research on the economic viewpoint of adopting sustainability in a factory has been done. Evans et al. in 2008, showed the results of sustainable manufacturing in the Ford Company; where operating costs were reduced between 30-40% [2]. The other companies commented on the introduction are also some examples of investing in sustainability and experiencing reductions in their operating costs and its environmental impact.

The difficulty of sustainable manufacturing is that every manufacturing process is different and needs to be uniquely analyzed. The work done by Seliger, Khraisheh and Jawahir in 2011 is a good example of this statement [4]. In their book “Advances in Sustainable Manufacturing”, they explain what sustainability in manufacturing is, the benefits that have for both the environment and the final revenue of the company and, also, how sustainability is achieved with some examples. At this point, after reading “Advances in Sustainable Manufacturing”, one realizes that sustainability in manufacturing can be explained in general but every case study in sustainable manufacturing is unique. In every single manufacturing process there are unique issues to face and, consequently, unique solutions for them.

However, research in sustainable manufacturing is helpful for encouraging companies to invest in sustainability. The research done in sustainable manufacturing has to show the advantages for both the company's revenue and the environment. Gaughran, Burke and Phelan in 2007 agreed that environmental sustainability is of significant relevance to all sectors and presents both risks and opportunities for businesses [5]. Elkington in 1998 goes further and sees sustainability in manufacturing as an opportunity for companies to increase their competitive strategy [6]. Sustainable advances in manufacturing ending up with lower operating costs increase the competitive advantage among other companies that are not investing in sustainability.

Previous work done to implement sustainable manufacturing in an existing process follows a determinate methodology [2]. I believe that implementing sustainable manufacturing is not something that can be done from one day to another and has to follow a process. The research done in sustainable manufacturing shows that the most common steps to follow to implement sustainable manufacturing are [2]:

- Walk factory to understand systems within the factory
- Qualitatively map manufacturing process
- Brainstorm likely material, waste and energy flows in processes
- Gather material, energy and waste data
- Determine constant and variable usage assets
- Empirical measurements
- Analyze data and identify improvement opportunities
- Rank improvement opportunities
- Implement opportunities

These are the general steps to follow when implementing sustainable manufacturing. However, all manufacturing processes are different and will require a detailed study. Also, depending on the tools used to study the manufacturing processes the steps followed will change. Every case study will follow different steps to reach sustainable manufacturing but the steps commented above can be used as guidance. In this project, the tool used to study the process is a simulation software. Therefore, the data gathering and other steps will be different from the detailed steps above. Also, depending on the manufacturing process characteristics some steps will have more importance than others, but in every case study the important steps will vary.

CHAPTER 2: Methodology

This chapter explains the methodology and the project development.

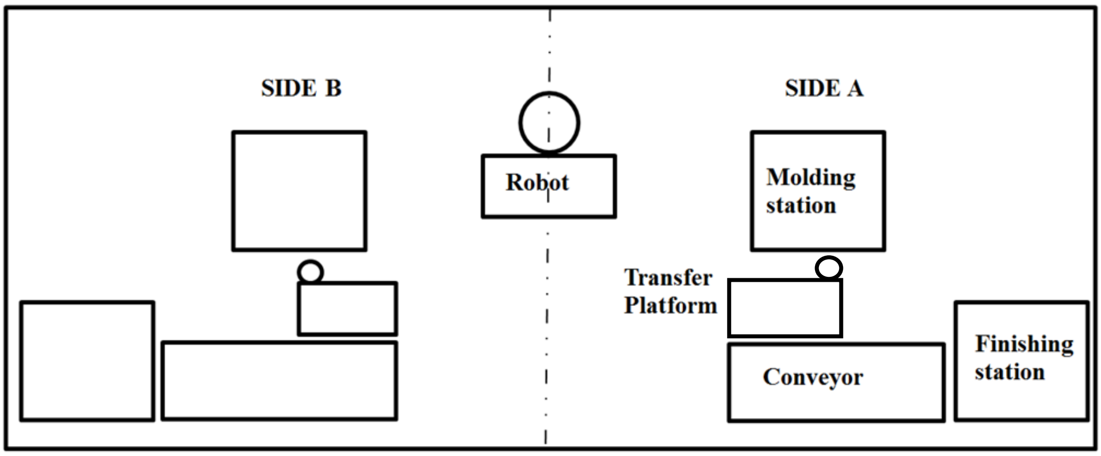
2.1 The Manufacturing Process

The first step of the development of the project was to find a suitable manufacturing process to study. The manufacturing process had to be a real manufacturing process from a factory. I had the opportunity to visit the factory Custom Castings Ltd., located in Winnipeg, Canada. After a first contact with the factory and the engineers of the factory I decided that I was going to choose a manufacturing process from Custom Castings.

Custom Castings is an aluminum supplier specialized in casting aluminum. They offer from the casting to CNC machining, surface coating, and other value-added processes such as heat treatment, pressure testing, and dynamic balancing. The factory layout is basically formed by work centers. The production depends on the customer's needs; the part follows different steps during the manufacturing depending on the customer's requirements. Thus, every part follows a different manufacturing process. However, in the factory there are two manufacturing processes established as cell layout, the Pulley Cell and the Robot Cell. In these manufacturing processes, parts follow the same steps during fabrication. In order to study a process and simulate a continuous production process, it is better to use a manufacturing process in a cell layout rather than in a work center layout. Therefore, the two options to consider for the project were the Pulley Cell and the Robot Cell. After observing both manufacturing processes and discussing which one was more suitable for this project, I agreed with Custom Castings' engineers that the best one seemed to be the Robot Cell because it offers more flexibility in production since two different parts can be produced at the same moment. Also, the Robot Cell is the largest manufacturing process in the Custom Castings and engineers want to improve its productivity.

The Robot Cell is formed by an aluminum furnace, a robot, two molding stations, two transfer platforms, two roller conveyors and two finishing stations. The Robot Cell is driven by the robot that absorbs melted aluminum from the furnace and pours it at either the right or left side, called A and B respectively. In each side there is a molding station, a platform that transfers the produced part from the mold to a roller conveyor, a roller conveyor and a finishing station (Figure 2.1). As seen in the Robot Cell's layout, there is an axis of symmetry in the layout of the manufacturing process. Both molding stations can produce different parts by changing the mold, thus, changing the manufacturing process time. However, long cycle time parts are produced in Side B and short cycle time parts in Side A. Thus, two operators, a caster and a finisher are required in Side A because the cycle time is shorter and one operator is not enough to handle all the process. Contrary, in Side B just one operator is required since the cycle time is longer.

Figure 2.1. Robot Cell's layout (Source: author)



The robot has to feed both molding stations when producing parts; therefore, the productivity of one side depends on what part is being produced in the other side and vice versa. Thus, I have to determine exactly which parts will be produced at the same time to have an accurate simulation. I studied the production of the parts CNH, Crary and Mcleroy because they are the parts that are being produced most often; for the process observing and data gathering easier. CNH and Crary are parts used in fan housing in agricultural vehicles. Figure 2.2 shows the part Crary finished in the factory and Figure 2.3 shows the part Crary assembled in an agricultural vehicle.

Figure 2.2. Part Crary (Source: author)

Figure 2.3. Part Crary assembled in an agricultural vehicle [7]

Mcleroy is used as a joint to fuse pipelines. In Figure 2.4, the part Mcleroy is ready to be sent to shipping at Custom Castings Ltd., and in Figure 2.5 the part Mcleroy is assembled in the vehicle used to fuse pipelines.

Figure 2.4 Part Mcleroy (Source: author)

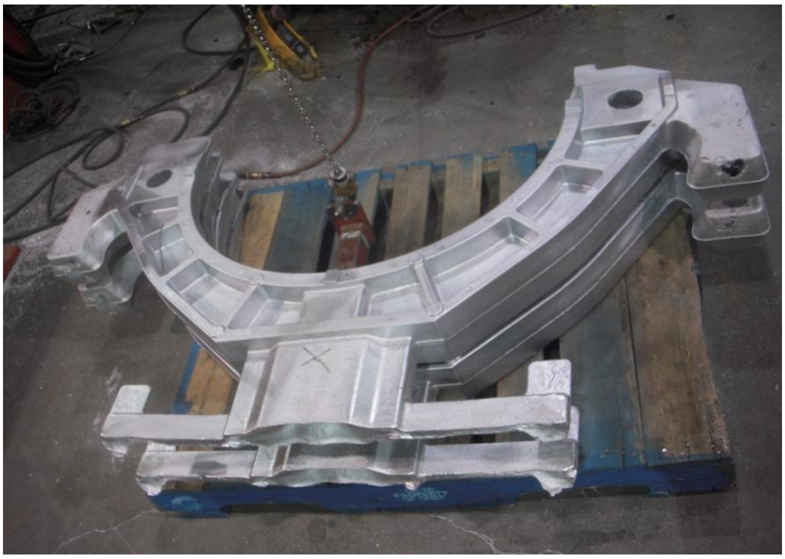
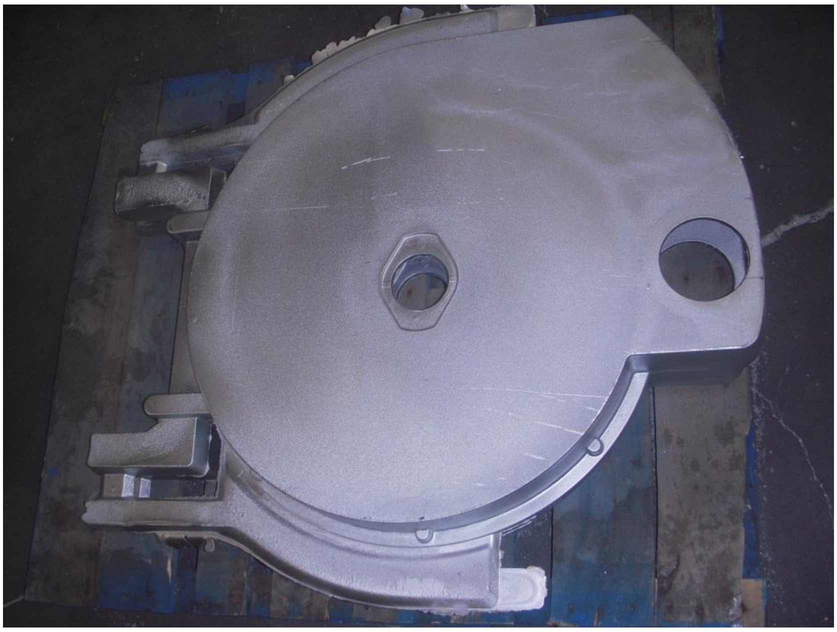


Figure 2.5 Part Mcleroy assembled in a vehicle to fuse pipelines [8]

Figure 2.6 Part CNH (Source: author)

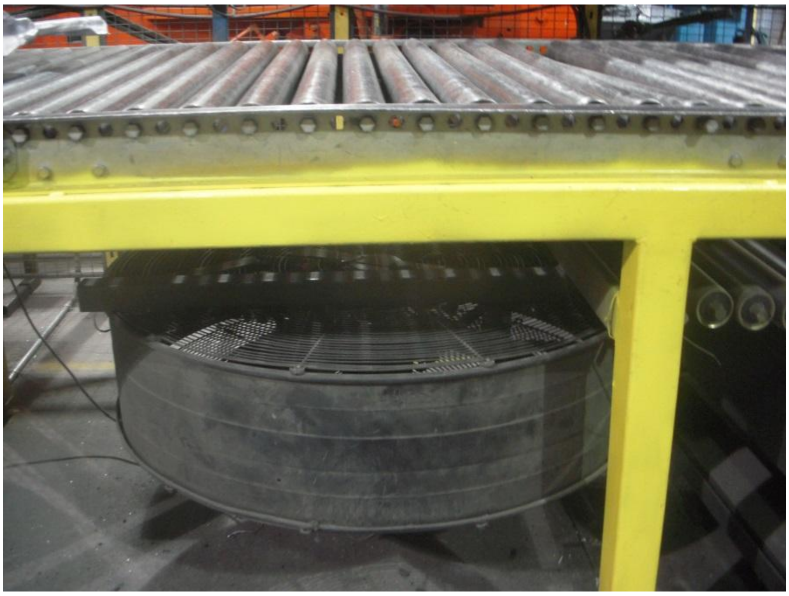


So, every part follows the same manufacturing process but requires different production parameters such as molding time, cooling down time, and finishing actions. The manufacturing process is explained step by step using the part Crary as a reference. However, the three parts studied and named above follow the same steps.

The manufacturing process starts with the robot idle and the liquid aluminum having the right temperature. First of all, the robot absorbs liquid aluminum from the furnace, lifts it and moves to one side, A or B, to pour the aluminum inside the two sprues of the mold. When the pouring process is done, the robot goes back to the furnace and the mold starts rotating from a horizontal position to a vertical position (90 degrees rotation). This rotation fills the mold with aluminum by the action of gravity. The mold remains vertical for a set time and then goes back to horizontal position. The time when the molding is vertical is called molding time, and varies for the three parts, having around two minutes of molding time when producing Crary and up to six minutes for Mcleroy. This difference in the molding time is what makes Crary a shorter cycle time than Mcleroy, Crary being produced in the right side and Mcleroy in the left side.

Then, the mold opens and the caster proceeds to activate the movement of the platform. The platform moves horizontally and allocates itself between both mold plates. When the top plate stops moving up, the caster has to unstick the part from the top plate of the mold. Then, the part falls down into the platform. The reverse movement of the platform is automatically done after a few seconds, transferring the part to the roller conveyor. The roller conveyor's function is to transfer the part to the finishing station and also to cool down the parts. There are fans located below the roller conveyor that cool down the parts during the transferring action (see Figure 2.7).

Figure 2.7 View of the fans located below the conveyor (Source: author)



When the parts are cool enough to be managed, the caster removes the extra material from the edges of the part using a saw. The caster cuts the extra material from the molding process leaving the part's edges sharp. Then, the finisher takes the part and proceeds to do the final operation of filing. The objective of this operation is to file the edges to leave them not sharp anymore. When the part is filed, the finisher puts it in a pallet ready to be packed and sent to shipping.

2.2 Data gathering and process observing

The first important step in this section was to observe the manufacturing process in the Robot Cell. The observing part is important to see the interaction between machines, the interaction between operators and machines, the flow of materials, and to spot the generated waste. The process observing was also important to see the movement that operators have to do while producing. Thus, the observing part of this section was to understand the manufacturing process in order to know which data would be necessary to build the model with the simulation software.

The data gathering started with taking times for all the different steps in the process. In order to model the manufacturing process with Witness, the cycle time for every activity is a required variable. So, I collected times for every activity during the production of Crary and CNH. Table 2.1 shows the collected times for every step in the manufacturing process.

Table 2.1 Average cycle time for machines in Crary and CNH processes

Action	CRARY (sec)	CNH (sec)
Robot Cycle	49	60
Molding Process	148	302
Cleaning MS	17	21
Platform Movement	12	12
Conveyor Movement	600	1800
Sawing	150	150
Filing	150	150

During my visits to the factory I was not able to see any production of the part Mcleroy, Custom Castings Ltd. produces only under demand and they had no Mcleroy parts required while I was studying the manufacturing process. However, I could access the historical production database of Custom Castings Ltd. and I could get some important information of the process for the three parts that I include in this project. The data I used from the database is included in the Appendix A. The data that I used from the database was to verify the data collected *in situ* for CNH and Crary. I used the historical database to verify the productivity, the defective parts generated, commonly known as scrap, and the total cycle time of the manufacturing process.

In order to quantify the improvements with a sustainable measure, I also collected information from the machines to know how much energy they consume. I looked up in the characteristics of every machine to know the Power of every machine. Then, with the hours of utilization (hours of production) from the database I can calculate the energy consumption using the following equation:

$$E = P * t$$

Other information required to analyze the energy consumption is the source of energy that machines use. All machines in the manufacturing process use electricity as a source of energy, so, since electricity is almost 100% generated with hydro energy I assumed that there were no CO_2 emissions in this manufacturing process. I decided not to use CO_2 emissions a sustainable measure because I did not have the necessary to calculate the emissions of the process and, anyways, I can assume that the emissions are low enough to not consider them.

CHAPTER 3: Modeling

This chapter is to explain the process of modeling using the knowledge and data gathered in last chapter.

3.1 Model Building

First of all, I had to decide how to model every element in the manufacturing process with the software Witness. Every machine in the manufacturing process would be represented by a machine in the model. So, the first thing to do was to insert machines in the model and locate them following the distribution of the real manufacturing process. There were machines for the furnace, the robot, the molding stations, the platforms, the conveyors, the saws and the files. Every machine was shaped to look like the machines in the real manufacturing process. When the layout with all the machines was ready, I proceeded to connect all the machines; including buffers represented as pallets after the conveyors.

The next element to define was the aluminum. Aluminum enters the process as aluminum bars. Then, the bars are melted in the furnace and the robot absorbs the melted aluminum and pours it in the molding station; where it is transformed from liquid to solid. It is difficult to represent the different physic states of the aluminum during the process, which is the reason why I assumed the aluminum is already melted in the furnace, so, aluminum can be represented as an unlimited part that is always ready to be pulled.

The left physical elements of the manufacturing process to define are the operators. Operators are the simplest elements to define just by adding a labor for every operator.

Next, I created variables to govern the model. I created two variables to determine the moment when operators have to refill the furnace with aluminum bars before the volume in the furnace is too low for the robot to absorb aluminum. I defined two variables more to determine the percentage of defective parts fabricated in the molding station that are sent to scrap. The last variable defined is to determine the cycle time for the robot. The cycle time for the robot depends on how much volume the robot absorbs. So, with big parts the robot will take more time to pour the aluminum in the molding station and with small parts the robot will last less time. Thus, I need a variable to define the robot cycle time that will change depending on where the robot is about to pour aluminum. Figures 3.1 and 3.2 show the model view with all elements.

Figure 3.1. View of the whole model

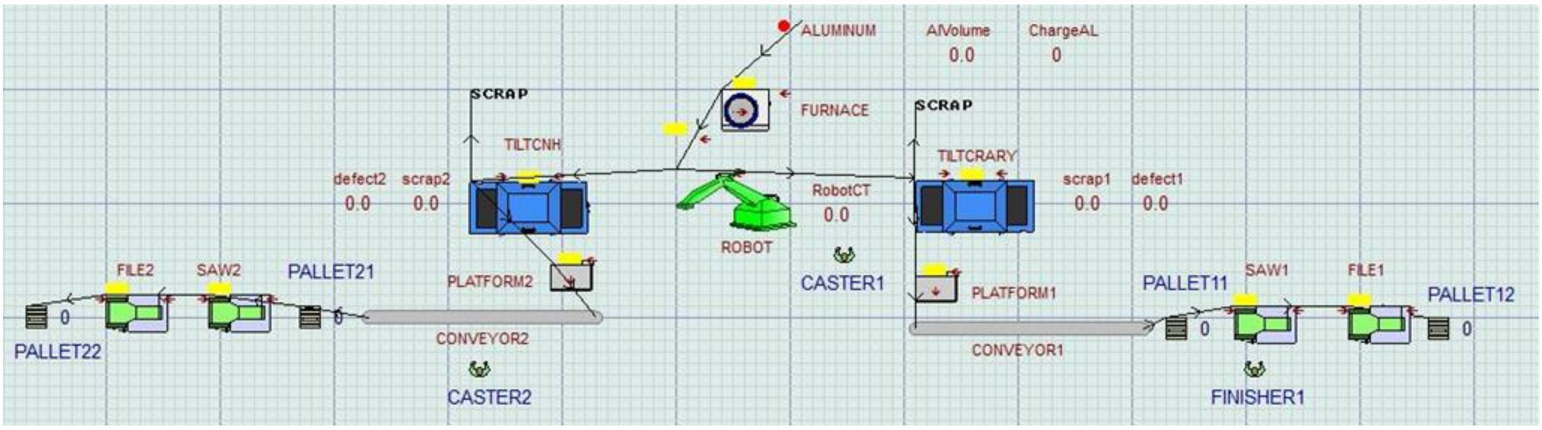
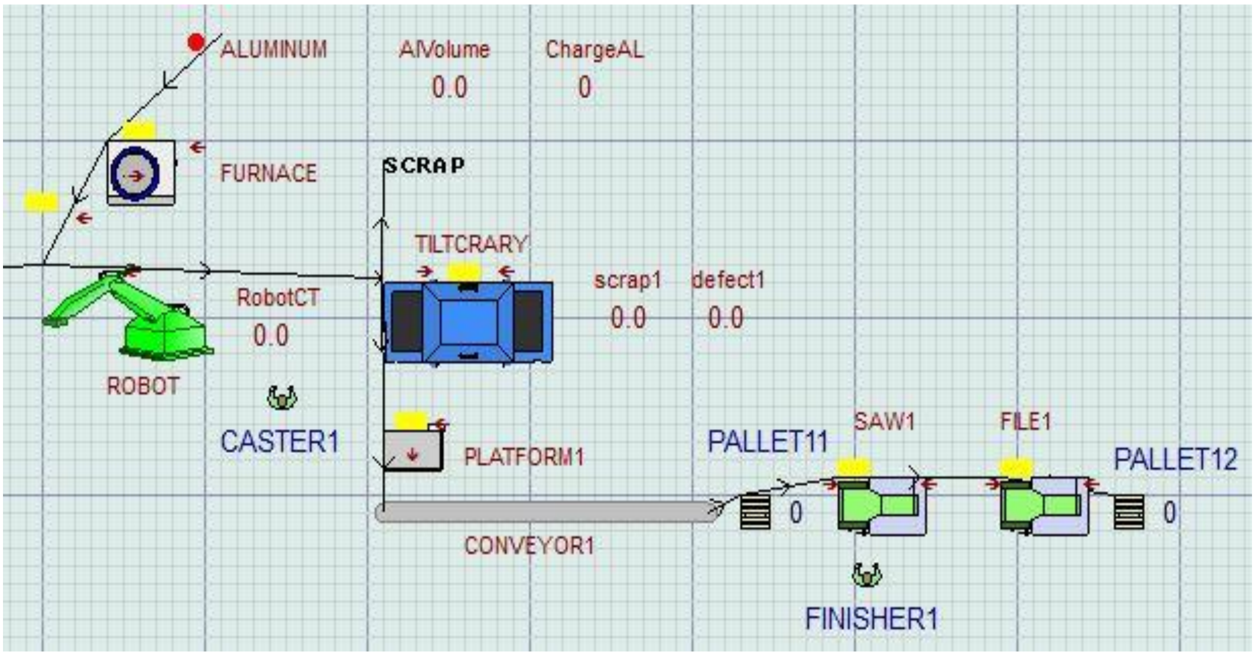


Figure 3.2 Zoomed view of the right side of the model



Moreover, there are some machines that have actions on start and actions on finish. These actions are made when the machine is about to start its cycle or about to finish it, respectively. In order to understand easily all the elements that are part of the model Table 3.1 and 3.2 includes every element and its characteristics.

Another important fact with the parameters of the machines is deciding the type of model that suits better reality. A model can be deterministic, all parameters are known and nothing changes with time, or stochastic, there is some randomness to consider that will change the results of every simulation. In this model, the machines are considered deterministic. After taking times of the machine's cycles I realized that times had little or no variation at all, so there was no need to consider randomness on those times. However, all operations that involve labor work frequently vary from operation to operation. Therefore, I considered that the cycle time for labor work had to follow a probability distribution defined with the data collected. Again, Table 3.1 also shows detailed information in these parameters.

Table 3.1 Current model elements and parameters

Element	Name	Type	Cycle Time (sec)	Comments
Machine	Furnace	Single	0	
Machine	Robot	Single	Variable	The cycle time is defined by the variable RobotCT
Machine	TiltCrary	Multiple Cycle	Molding: 148 Unstick part: 10 Cleaning: Poisson(45,34)	The cleaning follows a Poisson distribution
Machine	Platform1[1]	Single	15	
Labor	Caster1			
Transport	Conveyor1		Index time: 45	Index time defines the conveyor's speed
Buffer	Pallet11	Capacity: 50	Buffer to let the molding station produce if finishing stations go slower	
Machine	Saw1	Single	Poisson(150,32)	
Machine	File1	Single	Poisson(150,63)	
Buffer	Pallet12	Capacity: 2000	Pallet where parts are displaced to be send to shipping	
Labor	Finisher1			
Machine	TiltCNH	Multiple Cycle	Modling: 300 Unstick part: 10 Cleaning:	

[1] Number 1 references to the right side of the manufacturing process for Crary. Otherwise, number 2 references to the left side of the manufacturing process, CNH.

			Poisson(34,78)	
Machine	Platform2	Single	15	
Labor	Caster2			
Transport	Conveyor2		Index time: 90	
Buffer	Pallet21	Capacity: 50		
Machine	Saw2	Single	Poisson(150,54)	15
Machine	File2	Single	Poisson(150,23)	
Buffer	Pallet22	Capacity: 1000		
Variable	Scrap1	Real		
Variable	Defect1	Real		
Variable	Scrap2	Real		
Variable	Defect2	Real		
Variable	AlVolume	Real		
Variable	ChargeAL	Real		
Variable	RobotCT	Real		
Part	Aluminum	Active	Arrival: Unlimited (1 part/ sec)	

Table 3.2 Element rules: actions on start, actions on finish and labor rules

Element	Actions on Start	Actions on Finish	Labor rule
Furnace	If ALvolume is too low, ChargeAL changes Initialize variables scrap		
Robot	Gives a value to the variable RobotCT depending on which molding station is idle		
Molding Station			Labor needed for unsticking the part and the cleaning
Saw			Labor needed during the whole cycle
File			Labor needed during the whole cycle

There two more rules in the model to explain. The first one is a setup operation: the furnace has a setup operation that takes place when the variable ChargeAL changes. Then a labor is needed to refill the furnace with aluminum. The second one is a rule to transfer the melted aluminum. The Robot only starts its cycle when either molding station for Crary or CNH or both are idle.

3.2 Model Verification

When the model was ready to use I had to verify that it was working similarly to the real manufacturing process. First of all, I simulated the model five times obtaining the results in Table 3.3. The results show that there was not much variation between simulations; no more simulations were required. The simulations were on steady mode, where every machine is ready to operate and materials are ready to enter the process. Actually, in this manufacturing process aluminum is also considered as melted when the simulation starts. Simulations were defined as continuous production of 100 hours. Simulations are defined in that many hours to clearly see the time that every element spends in every state. The states for elements are busy, idle or blocked.

Table 3.3 First simulation results with current model

SIMULATION	1	2	3	4	5
CYCLE TIME CRARY (min)	5.2	4.8	5.3	5.0	5.2
CYCLE TIME CNH (min)	8.5	8.8	9.1	8.9	8.8
			EXPECTED TIMES		
		CT CRARY (min)		6	
		CT CNH (min)		10	

The obtained results were different from the expected results from the Custom Castings Ltd. database. Therefore, I studied the model again and I observe the manufacturing process again. I realized there was an action that I did not consider in the first model, the quality inspection. After a part goes out of the molding station, the caster takes some time to spot any existing defects in the part. The quality inspection is made right after the part is fabricated in order to not waste time adding value to a defective part that will be sent to scrap anyways.

Then, I modified the model adding another cycle to the molding station to represent the action to verify the part's quality. I simulated the model 5 times again and the obtained results were close enough to the expected results to accept the current model as verified. Table 3.4 shows the results for the simulation with the verified model. These numbers will be the reference to compare the results obtained in the further scenarios simulated.

Table 3.4 Results for current model

	CRARY	CNH
Acceptable	1043	600
Scrap	261	201
Scrap (%)	20	25
Cycle time (min)	6	10
Bottleneck	Molding Station	Molding Station
Productivity (parts/hour)	10.4	6

At this point, the model was operating close to reality and was ready to use with different scenarios. Next steps will be to decide which scenarios to create and modify the model for every scenario and simulate it to see the results.

CHAPTER 4: Scenarios Creation, Simulation and Analysis

The scenarios to increase the manufacturing process sustainability have been developed with the help of Custom Castings Ltd. Engineer Department. They wanted to see the results of the simulation for some scenarios. Also, I suggested my own ideas to modify the manufacturing process and see the results.

4.1 Scenario 1: Reducing the Scrap Generation Percentage

The first waste I spotted when I was observing the Robot Cell manufacturing process was the big amount of defective parts that were produced. I noted down the defective parts for Crary and CNH out of the acceptable parts. However, in order to have a higher accuracy on the percentage of scrap generated I used the Custom Castings Ltd. database as a reference.

The scrap generation percentage for Crary and CNH is, respectively, 20.2% and 24.85%. In other words, approximately one every five Crary parts is considered defective, while one every four CNH parts is considered not acceptable. Scrap generation is a waste of time and resources that has to be mitigated.

There are many reasons why a defective part is produced. The problem can be in the mold or process design. The design of the mold is not accurate enough and the flow of melted aluminum is different as expected. Also, another reason could be the temperature. The mold is too hot or too cold and the molding process is not being held in the appropriate operating conditions. Moreover, the problem can be in the mold cleaning process made by the caster. If there is any remaining material in the mold before pouring aluminum to fabricate the new part, the part can be produced with a spot or defect that will make the part not acceptable.

Scenarios are designed to modify the current model and see the results. Despite naming the reasons why a defective part is produced, this part is out of the scope of the project. The focus is on seeing the increase on the process sustainability by reducing the scrap generation. The model is used to simulate as close to reality as possible this scrap generation reduction.

The goal is to achieve only 5% of scrap generation in the production of both parts, Crary and CNH. In the current model, the variables defect and scrap govern the scrap generation for the process. In the current model they are set not to accept a part fabricated in the molding station every five parts for Crary, and every four parts for CNH. A 5% of scrap generation means fabricating only one defective part every 20 parts. Modifying the two variables, scrap and defect, for both sides of the manufacturing process will reduce the scrap generation to a percentage close to 5%. It will not exactly be 5% because the process considers a certain degree of randomness. The results of the simulation are shown in Table 4.1.

Table 4.1 Results for simulation in Scenario 1

	CRARY	CNH
Acceptable	1235	755
Scrap	61	37
Scrap (%)	4.7	4.6
Cycle time (min)	4.9	8
Bottleneck	Molding Station	Molding Station
Productivity var. (%)	+15.5	+20.5

In Scenario 1, the scrap generation is lowered below 5% in both sides of the Robot Cell resulting in an increase of productivity of 15.5% in the Crary manufacturing process and 20.5% in the CNH manufacturing process.

4.2 Scenario 2: Reducing the Cooling Down Time in the Conveyors

When the molding process is over, parts are transferred from the molding station to the finishing station through a conveyor. However, the objective of the conveyor is not only transporting but also cooling down the parts. Parts cannot be treated right after the molding process because they have a too high temperature, thus parts must be cooled down before arriving to the saw and the file.

The cooling down time is not the same for all parts; obviously, bigger parts will need more cooling down time than smaller parts. The average cooling down time for Crary parts is 10 minutes and the average cooling down time for CNH is 30 minutes.

The cooling down process is held by air fans located below the roller conveyor. The roller conveyor is made by rolls that let the air go through them (see Figure 2.7). I considered a waste of time the fact that parts have to spend a lot of time on the conveyors to cool down. The main objective of Scenario 2 is reducing this cooling down time by using a more powerful cooling down system that would reduce the cooling down time by 50%. Then, the cooling down time for Crary would be five minutes and for CNH would be 15 minutes.

The only modifications required in the model to simulate this scenario are changing the conveyors parameters. Conveyors are defined with an index time that represents the conveyors velocity. Conveyors are defined by a length in parts and the index time represents the time it takes a part to move from one position in the conveyor to the next [9]. Then, the higher the index time the slower the conveyor transports parts. Therefore, I reduced the index time in both conveyors by 50% and simulated it to see the results. Results are shown in table 4.2.

All scenarios have the current model as a reference. Then, in this scenario scrap generation is the same as in the current simulation. All scenarios are independent within each other.

Table 4.2 Results for the simulation in Scenario 2

	CRARY	CNH
Acceptable	933	586
Scrap	233	196
Scrap (%)	20	25
Cycle time (min)	6.4	10.2
Bottleneck	Labor	Labor
Productivity var. (%)	-11.8	-2.4

The simulation results were surprising. Increasing the conveyors velocity (reducing the cooling down time) resulted in a decrease in the productivity for both manufacturing processes, Crary and CNH. The first thing to notice was the change in the bottleneck. The bottleneck in the current model is the molding station because is the longest cycle time in the Robot Cell. Then, if the bottleneck moves to another element means that the molding station is being blocked at some points during production. To be more accurate, what happened in the simulation for Scenario 2 is that the molding stations were waiting for labor to finish their operations. Labor were busier than in the current model because parts were arriving faster in the finishing station, and even having the molding station a higher priority than the finishing station resulted in a lack of labor in the molding station. In other words, molding stations were waiting for the casters while they were taking care of the finishing operations in the saw for Crary and in the saw and in the file for CNH.

There is a big rule in Project Management activities, when increasing the cycle time in the bottleneck, in this case the molding station; the cycle time of the whole manufacturing process increases too. Therefore, next scenario is thought to find a solution for this situation and change the bottleneck to the molding station again.

4.3 Scenario 3: Reducing the Cooling Down Time and Adding Labor

The problem with scenario 2 was the movement of the bottleneck from the molding station to labor. The lack of labor can be solved by adding labor or reassigning tasks.

In the left side of the Robot Cell, there is only one labor, a caster. Thus, there is no chance to reassign tasks and the only possible solution in order not to have a lack of labor is adding a finisher who will take care of the sawing and filing operations.

In the right side of the Robot Cell, there are two labors, a caster and a finisher. In the current model configuration, the caster is taking care of the molding station and also the sawing operations. The finisher is taking care of the filing operations only. Obviously, the caster was the bottleneck in the simulation for Scenario 2. Therefore, in Scenario 3 there is a reassignment of tasks; the finisher is taking care of the finishing operations, sawing and filing, while the caster is taking care of the molding station.

To sum up, the modifications to simulate Scenario 3 are: adding a finisher in the left side to take care of the saw and the file, and reassigning tasks in the right side. The results for this new simulation are shown in Table 4.3.

Table 4.3 Results for simulation in Scenario 3

	CRARY	CNH
Acceptable	1098	656
Scrap	275	219
Scrap (%)	20	25
Cycle time (min)	5.5	9.15
Bottleneck	Molding Station	Molding Station
Productivity var. (%)	+5	+8.5

With these new modifications productivity is increased by 5% in the Crary manufacturing process and by 8.5% in the CNH manufacturing process. However, the increase in the CNH manufacturing process is thanks to an extra worker. Thus, an economic assessment is required not only for the new cooling down system that would lower the cooling down time by 50%, but also for the extra labor costs in salary and other expenditures. The most interesting result in this scenario is for the Crary process, where improving the cooling down system and reassigning tasks between labors increases the productivity by 5%.

4.4 Scenario 4: Reducing Mcleroy Mold Cooling Down Time

Scenario 4 is the only scenario for Mcleroy parts due to the lack of information. During my visits at Custom Castings Ltd. I did not have the chance to see the production of Mcleroy parts. However, Custom Castings Ltd. engineers were concerned about the mold cooling down time.

Mcleroy parts are the biggest parts produced in the Robot Cell with a 155 pounds weight. These parts require a high temperature in the mold during the molding process. The high temperature is a problem when pouring the aluminum; then, the mold must be cooled down after the molding process and before the robot pours aluminum again.

The current “cooling down system” does not really exist for only leaving the mold opened while it cools down itself. Engineers from Custom Castings Ltd. have thought about incorporating a cooling down system that uses forced air would reduce the cooling down time. Currently, the cooling down time of the mold takes up to 12 minutes.

Again, the objective of this scenario is to reduce this cooling down time and analyze the results to see if a further installation of a cooling down system would be feasible. The objective is to reduce the cooling down time of the mold by 50% by adding a fan.

In this scenario, I use data from the database and I have to estimate times for the cycle times because I have no data for all of them. In the database I can find the part cycle time, that represents the cycle time for the molding process because it is the bottleneck. The estimation for the robot cycle time is made using the required time for Crary and CNH and the difference of weight between them and Mcleroy parts. The finishing operations are not critical in the process; always require less time than the molding process and the time used for them is not relevant in this simulation. Results for this simulation are shown in Table 4.4.

Table 4.4 Results for simulation in Scenario 4

MCLEROY	Current	Scenario 4
Acceptable	174	214
Cycle time (min)	34.5	28
Bottleneck	Molding Station	Molding Station
Productivity var. (%)		+18.7

In Scenario 4 there is a heavily increase in productivity because the focus is on saving time in the bottleneck. All time saved in the bottleneck is time saved in the whole manufacturing process. Scenario 4 increases 18.7% productivity. However, since the Mcleroy model is not accurate enough to reality due to lack of information, the accuracy of the results could be affected. Anyways, it is pretty obvious that saving waiting time in the bottleneck is an operation that would enhance the manufacturing process performance.

CHAPTER 5: Results and Discussion

5.1 Recommendations

The results obtained with the scenarios simulation and analysis led to different recommendations on the manufacturing process.

The results obtained with Scenario 1 pointed out that the scrap generation the main focus of waste in this manufacturing process. Therefore, efforts to reduce the number of defective parts are required in order not to waste time and resources producing parts that will be sent to the furnace again. The advantage of having a model of the process is that variables can be changed to any number and the results can be helpful when developing an economic assessment for the implementation of a different process to reduce scrap generation. In Scenario 1 there are the results lowering scrap generation down to 5%, but if this reduction is too ambitious for the first intent to reduce scrap generation, a first economic assessment can be done with the productivity variation using another percentage of scrap generation. The model gives the chance to Custom Castings Ltd. to modify variables under their own preferences. The flexibility of the model can help the company to do an economic assessment on every modification and see the expenditures and the expected increase in the income.

Scenario 2 and Scenario 3 go together and can also help to determine if a new cooling down system for the conveyors would be economical feasible for the company. With the simulation, the new productivity rates are higher than with the current manufacturing process. However, again an economic assessment is needed to see if the modifications are worth the investment in that new system. The investment would require a new cooling down system for the conveyors, a reassignment of worker's tasks, and also a new worker required in the Robot Cell.

Scenario 4 is the only one for Mcleroy parts. The increase in productivity of implementing a cooling down system for the mold is important. Productivity increases up to 18.7% when reducing the cooling down time by 50%. The cooling down system would force air to cool down the mold faster. Again, an economic assessment of the cooling down system and the increase in the revenue is required to determine the feasibility of the operation.

Finally, I would personally recommend Scenario 1 and Scenario 4 to study for implementation. The scrap generation is considered a worse waste than the waiting time for cooling down parts. When a manufacturing process is producing scrap, it is using resources (labor, materials, and energy) to fabricate a part that will not be acceptable and will not generate revenue. Therefore, I would recommend focusing the effort on scrap generation for Crary and CNH parts. Scenario 4, for Mcleroy parts, show the great increase in productivity if the waiting time for cooling down the mold is reduced. The cooling down system could be an air fan that would force air into the mold; nothing too sophisticated and expensive. Thus, since the productivity is heavily increased in this scenario, I would recommend focusing effort on the cooling down time for the mold in the Mcleroy parts production.

5.2 Sustainability

The increase in sustainability for the Robot Cell is calculated using the energy as a sustainable measure. During fabrication, machines consume energy to develop the operations. The highest consumption of energy in the process is in the furnace. The furnace has to melt bars of aluminum continuously and then maintain a minimum temperature to keep the aluminum liquid and in the right state to be poured in the molding station. The energy consumed in the furnace is huge compared to the rest of machines. I will assume the energy consumed in the furnaces is the energy consumed in the manufacturing process.

The furnace consumes 71 kW per ton of aluminum melted. Using the weight for Crary, CNH and Mcleroy parts and the time used to produce one part I will calculate the energy consumed per part in the current model, and also for all Scenarios (see supporting calculations in Appendix B). Table 5.1 shows the results for the energy consumption in all cases.

Table 5.1 Energy consumption for all scenarios

PART	Power (kW)	Energy Current (Wh)	Energy Scenario 1 (Wh)	Energy Scenario 3 (Wh)	Energy Scenario 4 (Wh)
Crary	531.47	53.15	43.4	48.72	-
CNH	1288.40	214.73	171.79	196.48	-
Mcleroy	4992.55	2870.72	-	-	2329.86

The consumption for the furnace depends on the amount of aluminum melted. All parts studied have a different weight; thus, require a different power. Power is calculated with the furnaces consumption and the parts weight. Then, with the power required for every part and the cycle time required to produce one part of each kind I can calculate the amount of energy in kWh necessary to produce one part in every different scenario.

Table 5.2 shows the percentage reduction in energy consumption while producing a part in every scenario.

Table 5.2 Percentage variation in energy consumption

ENERGY SAVED	Scenario 1 (%)	Scenario 3 (%)	Scenario 4 (%)
Crary	-18.34	-8.33	-
CNH	-20	-8.5	-
Mcleroy	-	-	-18.84

We can see from the results that the highest reductions in energy consumption are in Scenario 1 and Scenario 4. With these results recommendations for implementation on Scenario 1 and 4 are stronger. The improvements studied in Scenarios 1 and 4 not only increase the productivity, thus, the revenue, but also reduce the energy consumption increasing the sustainability of the Robot Cell.

CHAPTER 6: Conclusion

The project objective was to increase the Robot Cell's sustainability by modifying the manufacturing process. The scenarios created and simulated have enhanced the manufacturing process efficiency, thus, lowering the energy consumption per part produced.

This project opens the opportunity for Custom Castings Ltd. to start thinking on sustainable manufacturing not only in the Robot Cell, but in all their processes. As commented in the introduction, sustainable manufacturing has benefits for the environment and also for the company.

Further work will be to do an economic assessment of all modifications suggested in the project for implementation. Modifications can increase the revenue but have also extra expenditures that must be studied before the implementation. Also, the model can be used to study further possible scenarios that engineers in Custom Castings Ltd. would like to simulate. The model is an opportunity for the company to study further modifications, plan production, and see the production performance of parts before actually start producing them. Simulation is a useful tool for manufacturing because running a production line is a very expensive operation; therefore, the opportunity to first simulate the process in a computer software is valuable in the manufacturing sector.

Further steps would be to study all parts produced in the Robot Cell. For all parts the methodology would be the same as the one followed in this project. First of all gather data to use in the model, verify the model, create scenarios, and simulate and analyze them.

The project is just the beginning of implementing sustainable manufacturing in a factory and the purpose is to show the benefits for the company to continue investing and researching in sustainable manufacturing for its manufacturing processes.

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APPENDIX A. Custom Castings Ltd. Database

This appendix is contains the data I have used from the Database of Custom Castings Ltd. during the development of the project. Every row in the tables is a day of production during 2013.

A.1 Crary Database

Shift hours	Parts per shift	Parts per hour	Scraped	% Scraped
4	2	1	37	94.87
8.5	39	5	33	45.83
3	11	4	9	45.00
8	56	7	12	17.65
5	25	5	15	37.50
7	38	5	12	24.00
5.5	30	5	10	25.00
7	20	3	33	62.26
4	15	4	26	63.41
5.5	20	4	14	41.18
7.5	40	5	10	20.00
7	25	4	20	44.44
3.5	22	6	5	18.52
1.5	10	7	0	0.00
6.5	42	6	4	8.70
6.5	40	6	8	16.67
3.25	21	6	5	19.23
4	27	7	2	6.90
3.25	26	8	0	0.00
6	30	5	14	31.82
8	33	4	26	44.07
7.5	29	4	25	46.30
6.5	31	5	17	35.42
5.5	27	5	17	38.64
7.5	45	6	7	13.46
4	12	3	10	45.45
1.5	13	9	2	13.33
3	19	6	6	24.00
6.5	34	5	5	12.82
4.5	15	3	17	53.13
7.25	44	6	9	16.98
2	5	3	14	73.68
5	23	5	13	36.11
6.5	38	6	12	24.00
6.5	29	4	15	34.09
1	2	2	6	75.00
8	54	7	4	6.90

3	12	4	12	50.00
4	27	7	7	20.59
7.5	47	6	11	18.97
5.5	33	6	5	13.16
3	25	8	1	3.85
4.5	27	6	12	30.77
7	32	5	8	20.00
7	30	4	10	25.00
5	28	6	9	24.32
5.5	30	5	13	30.23
7	38	5	11	22.45
3	7	2	12	63.16
8	59	7	13	18.06
4.5	30	7	4	11.76
5	16	3	17	51.52
1	3	3	6	66.67
4	15	4	11	42.31
9	61	7	6	8.96
5.5	30	5	19	38.78
7.5	34	5	17	33.33
7.5	26	3	26	50.00
1	3	3	4	57.14
7	36	5	12	25.00
7.5	38	5	1	2.56
7.75	42	5	7	14.29
3	16	5	3	15.79
6.5	38	6	2	5.00
7.5	30	4	20	40.00
1.5	10	7	2	16.67
8.5	50	6	11	18.03
6.5	25	4	23	47.92
7.5	39	5	12	23.53
2	14	7	2	12.50
4	26	7	6	18.75
2	6	3	7	53.85
6	28	5	13	31.71
7.75	22	3	23	51.11
7.5	42	6	12	22.22
7.5	22	3	30	57.69
7.5	38	5	15	28.30
4.5	36	8	4	10.00
7	50	7	16	24.24
8	34	4	28	45.16
3	14	5	10	41.67
3.5	23	7	6	20.69
8	51	6	10	16.39
7	27	4	17	38.64

6	12	2	22	64.71
5.5	30	5	11	26.83
8	56	7	12	17.65
4	24	6	24	50.00
6.5	40	6	13	24.53
4	3	1	17	85.00
7.5	51	7	11	17.74
5.5	31	6	12	27.91
8	48	6	10	17.24
8.5	66	8	8	10.81
6	42	7	8	16.00
3.5	33	9	3	8.33
6	48	8	6	11.11
5	40	8	13	24.53
8	50	6	12	19.35
8	57	7	17	22.97
7.5	50	7	13	20.63
6	35	6	9	20.45
3	13	4	10	43.48
8	51	6	14	21.54
3.5	23	7	10	30.30
8	50	6	9	15.25
3.5	24	7	9	27.27
5.5	30	5	17	36.17
6	34	6	11	24.44
8	60	8	9	13.04
3.5	25	7	7	21.88
7	40	6	17	29.82
3.5	25	7	11	30.56
3	22	7	7	24.14

A.2 CNH Database

Shift hours	Parts per shift	Parts per hour	Scraped	% Scraped
4	6	2	3	33.33
8	13	2	6	31.58
7	12	2	4	25.00
8	16	2	5	23.81
5.5	4	1	8	66.67
5	7	1	4	36.36
6.5	6	1	10	62.50
6	10	2	3	23.08
9	17	2	5	22.73
10	22	2	2	8.33
3	2	1	3	60.00

8.5	16	2	4	20.00
8.5	14	2	4	22.22
8	12	2	4	25.00
7	12	2	5	29.41
9	19	2	2	9.52
7	10	1	6	37.50
6	10	2	4	28.57
8	13	2	5	27.78
7	11	2	4	26.67
6	8	1	4	33.33
8	16	2	3	15.79
6	9	2	7	43.75
3	5	2	2	28.57
7	9	1	8	47.06
6.5	12	2	3	20.00
6	12	2	2	14.29
7	13	2	3	18.75
5	7	1	3	30.00
8	13	2	6	31.58
5	7	1	4	36.36
4	2	1	7	77.78
6.5	10	2	6	37.50
6	4	1	8	66.67
6	8	1	5	38.46
5.5	1	0	9	90.00
7	8	1	6	42.86
7	13	2	3	18.75
8	16	2	2	11.11
4	2	1	6	75.00
7.5	4	1	11	73.33
5.5	10	2	2	16.67
8.5	11	1	6	35.29
8.5	14	2	3	17.65
8	15	2	1	6.25
2	4	2	0	0.00
6.5	11	2	3	21.43
6	11	2	1	8.33
8	17	2	1	5.56
8.5	13	2	5	27.78
4.5	8	2	5	38.46
6.5	15	2	2	11.76
6	9	2	4	30.77
4.5	11	2	1	8.33
6.5	14	2	4	22.22
7.5	15	2	2	11.76
7	15	2	1	6.25
2	2	1	2	50.00

8	16	2	4	20.00
8	17	2	6	26.09
8	17	2	3	15.00
7	15	2	5	25.00
6.5	15	2	1	6.25
2.5	3	1	3	50.00
8	18	2	1	5.26
6	12	2	2	14.29
8.5	19	2	1	5.00
6	15	3	1	6.25
6	11	2	3	21.43
7.5	14	2	2	12.50
5	10	2	3	23.08
2.5	4	2	1	20.00
8.5	18	2	1	5.26

APPENDIX B. Supporting Calculations

This appendix is to show the data and the equations used in the calculations of the energy consumed. The results of the calculations are in the body of the project in tables 10 and 11.

	Weight (pounds)	Current CT (min)	Scenario 1 CT (min)	Scenario 3 CT (min)	Scenario 4 CT (min)
Crary	16.5	6	4.9	5.5	-
CNH	40	10	8	9.15	-
Mcleroy	155	34.5	-	-	28

$$P_{req} = 71\frac{kW}{ton} * \frac{ton}{1000\ kg} * \frac{kg}{2.2046\ pounds} * weight$$

$$E_{con} = P_{req} * CycleTime$$